A Fuzzy Based Solution for Improving Power Quality in Electric Railway Networks

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Received: October 13, 2011 Accepted: October 19, 2011 Published: Feburary 1, 2012
doi:10.5539/mas.v6n2p22 URL: http://dx.doi.org/10.5539/mas.v6n2p22

Abstract

There are many fundamental differences between electric traction networks and other industrial supply networks in terms of dynamic behavior and static characteristics. For example, the time variation of a load causes voltage variations in a supply network, which results in variations of power flow in the supply network. Today, reactive power compensators are the most practical solutions for keeping voltage levels in normal boundaries. In this paper, with the aim of fuzzy logic, a method for compensating reactive power losses in electrical traction networks is proposed. The proposed method has many advantages such as decreasing the reactive power compensation costs, determining the optimum switching step of capacitor banks and deducing the losses in electric traction networks.

Keywords: Reactive Power, Electric Traction Networks, Railway Electrification, Fuzzy Logic

1. Introduction

Reactive power creates numerous problems in electric railway supply networks. Because of the particular characteristics of electric traction loads, the problems have higher intensity in railway supply networks than other types of electric supply networks. Reactive power can be compensated by implementation of active or static methods. Nowadays a common method, in most electric substations, is to use shunt capacitors (Chin H. C., & Lin Wh. M., 1994; Baghzouz Y., & Ertem S., 1995). The advantages and disadvantages of this method are explained in Table 1.

Allocation of these shunt capacitors in the network shall be according to the power network topology. Electric railway networks has individual characteristic such as time variant and location variant trains' power demand. So, this paper proposed improving power quality based on optimization of capacitor allocation in electric railway power supply network. In next sections, this solution is expressed.

2. Calculation of the Capacitor Power for Power Factor Correction

In three phase circuits, the power factor correction capacitor is installed as shown in Figure 1. The capacitor power can be calculated from equation (1) (Chin Hong-Chan, & Lin Whei-min, 1996).

$$Q_C = P_L\left(\tan\phi_o - \tan\phi_C\right) \tag{1}$$

In Figure1, phases *a* and *b* are the supplying overhead lines in both sides and C_1 and C_2 are the shunt capacitors. In a traction substation, the power factor is obtained from

$$Cos\varphi = \frac{W_{P\varepsilon}}{\sqrt{{W_{P\varepsilon}}^2 + {W_{Q\varepsilon}}^2}} \tag{2}$$

Where $W_{P\varepsilon}$ is the measured active power (kWh) and $W_{Q\varepsilon}$ is the measured reactive power (kvarh) (Baghzouz Y., & Ertem S., 1990). In the electric railway supply circuit, by considering the circuit, the capacitor power can be calculated from

$$Q_C = P_L(\tan\phi_O - \tan\phi_C)\frac{1}{1-P_O} \quad (3)$$

Where P_o is the circuit no-load probability. Generally, implantation of capacitors in three phases (between the lag, lead or no-load phases) is not necessary. Capacitors are usually installed in circuits in the following ways (Shirmohamadi D., et al., 1988):

I. If $I_{lead} >> I_{lagging}$ capacitor in lag and lead phases

II. If $I_{lead} << I_{lagging}$ capacitor in no-load and lag phases

III. If $I_{lead} = I_{lagging}$ capacitor in the lag phase

In case II, it is also possible to install the capacitor in the lead phases; however, this would be harmful to the network power factor.

3. Cost Equation

After calculating the loss and considering the required capacitor for reactive power compensations, the cost value (Chin Hong-Chan, & Lin Whei-min, 1994) can be acquired from

$$f = K_p P_{Loss} + \sum_{j=1}^{k} K_j Q_j \quad (4)$$

where K_P is the cost of the reactive losses, P_{loss} is the total losses of the overhead network in each step of capacitor allocation, J $(=1,2,...,K)$ is the selected bus for capacitor installation, Kj is the minimum cost of possible circumstance coefficients plus the installation and maintenance, and Q_j is the total power of the existing capacitors.

4. Problems' Constraints

Each optimization problem usually includes constraints. The operational constraint is the voltage amplitude in traction substations, which must be kept in the permitted limits of

$$v_{min} \leq |v_i| \leq v_{max} \quad (5)$$

where V_i is the voltage of substation i, and V_{max} and V_{min} are the maximum and minimum permitted voltages, respectively.

5. Determining the Required Capacitor Power via Fuzzy Logic

Various capacitor allocation methods are implemented for minimization of the reactive power losses. One of the implemented methods is based on Fuzzy logic that can assign sensitive points for capacitor installation. A Fuzzy-logic based solution benefits from high accuracy, response rate and μp (Chin Hong-Chan, & Lin Whei-min, 1996).

In this research, the active power losses are used as the static input data to the fuzzy sensitive system of voltage in the electric train location (or bus).

It should be noted that the minimum membership functions of the reactive power and bus voltage sensitiveness have assigned the required capacitor power in each operation period. Thus any increase in the losses results in an increase in the value of the membership function. Also, any decrease in the losses results in a decrease in the value of the membership function. One of the useful equations for demonstration of the function is

$$\mu_p(i) = e^{-\frac{wP(Li)}{P_{Loss}}} \quad (6)$$

where w is the weight coefficient obtained from

$$w = \frac{P(Li)}{P_t} \quad (7)$$

where $P(L_i)$ is the active power losses in the train to the substation circuit, P_t is the total active power of other trains and P_{Loss} is the sum of the active power losses.

In order to find a solution for the bus voltage sensitiveness problem, in case of large voltage deviations, a low membership function is taken into account. Thus, the relative membership function can be expressed as

$$\mu_v(i) = e^{-w\left[\frac{v(i)-1}{v_{max}-v_{min}}\right]^2} \quad (8)$$

where $v(i)$ is the voltage of bus i, V_{max} is the maximum voltage limit, V_{min} is the minimum voltage limit and w is the weight coefficient acquired from equation 7. Generally for calculating the required capacitor power, both the bus voltage sensitiveness (as in Figure 2) and the active losses (as in Figure 3) factors should be considered. Therefore it becomes necessary to define a decision function that contains μs.

For finding the candidate locations for capacitor installation, both the active losses and the voltage sensitiveness factor are vital. Thus, considering the mentioned factors, a comprehensive decision function can be defined as

$$\mu_s(i) = \min\{\mu_v(i), \mu_p(i)\} \quad i=1, 2, \ldots, m \quad (9)$$

The minimum point of the membership function is selected as the candidate location for capacitor installation. The low value of μ_s indicates that the point of the overhead network has a very high sensitiveness to voltage deviations and power losses.

6. Explanation of the Fuzzy-based Procedure

Figure 4 explains the Flowchart of the Optimum Capacitor Allocation Procedure in the Electric Railway Overhead Network.

The main steps of this procedure are (Ng H. N., et.al, 2000):

i. Calculating the network load flow, determining voltages and losses of the buses, and calculating μ_p and μ_v.

ii. Distinguishing the candidate point (i.e. bus *M*) by considering the minimum decision function.

iii. Determining the capacitor power, which satisfies both the voltage and the cost constraints, after performing the capacitor installation steps in bus *M* and running the load flow. If any capacitor power value does not satisfy voltage constraints of a selected bus, the bus should be eliminated from the list of candidate buses.

iv. After eliminating bus *M* from the decision function and setting the calculated capacitor on it, the load flow is run and a new decision function is formed without considering bus *M*.

v. Distinguishing the new candidate bus from the new decision function, then jumping to step iii.

vi. The flowchart should be taken into account until it satisfies the voltage constraints. Also decreasing the cost value in an instant step from proceeding is lower than the defined minimum value for all buses.

One of the advantages of the demonstrated flowchart is that it considers the voltage constraints, while minimizing the active losses and therefore the corresponding cost function. In addition, the introduced procedure is capable of solving minimization of active losses problem (i.e. minimization of the cost function). The procedure can also determine the location and rate of the required capacitor for installation in the overhead network, provided that the bus voltages are in the permitted limits.

7. Simulation Results and Comparisons

7.1 The Required Information

A radial supply feeder is considered and presented in Figure 5. The feeder has 9 load buses (an electric train per block), a nominal voltage of 25 kV and a rated power of 15 MVA.

The loads and the feeder data of the assumed overhead network are shown in Tables 2 and 3. Other data presented are: V_{min} =0.9 p.u., V_{max} =1.1 p.u. and kp =168 \$/kW.

In Table 2, the maximum capacitor power should not exceed the total reactive power (i.e. 4186 VAR). Therefore, regarding the existing capacitor and the minimum cost conditions (including the maintenance, installation and purchase costs), the capacitor step value and the corresponding cost coefficients can be acquired from Table 4. The network load flow results before compensation via the presented procedure are shown in Table 5.

It is clear from Table 6 that the costs and total losses in the presented procedure have more appropriate values than the referenced value in (Chin H. C., & Lin Wh. M., 1994).

8. Flowchart Implementation Results

According to Table 7, the probable rates of the capacitors are obtained by considering the corresponding cost coefficients in every step of the calculations. The voltage magnitudes for each selected item are shown in Table 8.

9. Conclusion

An appropriate method for determining the capacitors rates in each step, by considering the voltage magnitude constraints and the cost of losses, was proposed. In the proposed method, by setting the capacitor conditions in each period of operation and considering the absorbed power from each substation and the number of trains in each line, it became possible to ensure the improvement of the power quality index of the electric railway networks. In addition, the proposed Fuzzy-based solution had many advantages such as optimization of the compensation steps and reduction of the compensation costs.

Acknowledgement

The authors would like to thank Mr. H Zafari for his assistance to improve the contents of this paper.

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Table 1. Advantages and disadvantages of compensating the reactive power via shunt capacitors

Disadvantages	**Advantages**
-Insufficient life cycle	-Improvements of network utilization coefficient
-Instability during faulty conditions	-Deduction of losses
-Increased switching over voltages	-Power supply quality improvement
-Accretion in shunt resonance occurrence probability	-Deduction of negative sequence component
	-Improvement of Total Harmonic Distortion (THD) factor
	-Simple installation

Table 2. Load data of assumed overhead network

Number of Bus	P (KW)	Q (KVar)
1	460	1840
2	340	980
3	446	1790
4	1840	1598
5	600	1610
6	110	780
7	60	1150
8	130	980
9	200	1640

Table 3. Feeder data of assumed overhead network

Primary Bus (i)	Final Bus (i+1)	R(Ω)	X(Ω)
0	1	0.1233	0.4127
1	2	0.014	0.6051
2	3	0.7463	1.205
3	4	0.6984	0.6084
4	5	1.9831	1.7276
5	6	1.905	0.7886
6	7	2.0552	1.164
7	8	4.7953	2.716
8	9	5.3434	3.0264

Table 4. Variable choices of capacitor rates and corresponding cost coefficients

J	Q	K_i($/kvar)	J	Q	K_i($/kvar)
1	150	0.5	15	2250	0.197
2	300	0.5	16	2400	0.17
3	450	0.253	17	2550	0.189
4	600	0.22	18	2700	0.187
5	750	0.276	19	2850	0.183
6	900	0.183	20	3000	0.18
7	1050	0.228	21	3150	0.195
8	1200	0.17	22	3300	0.174
9	1350	0.207	23	3450	0.188
10	1500	0.201	24	3600	0.17
11	1650	0.193	25	3750	0.183
12	1800	0.187	26	3900	0.182
13	1950	0.211	27	4050	0.179
14	2100	0.176	---	---	---

Table 5. Bus voltage results

J	Q	Voltage (the defined method in this paper)
1	0.993	0.9929
2	0.987	0.9874
3	0.963	0.967
4	0.984	0.9482
5	0.917	0.9175
6	0.907	0.908
7	0.889	0.8892
8	0.859	0.8593
9	0.838	0.8382

ISSN 1913-1844 E-ISSN 1913-1852

Table 6. The results of comparing the presented procedure with reference value

Reference (Chin H. C., 1994)			Defined method in this paper					
119,736			119007.4					Total losses($/kvar)
707			701.66					Total losses(kW)
9	5	4	9	8	5	4	3	Compensated buses
900	2500	2100	900	300	1800	450	2400	Q_c(kvar)

Table 7. Variable choices of capacitor rates and the corresponding cost coefficients

J	Q	Kj($/kvar)
1	150	0.5
2	300	0.5
3	450	0.253
4	600	0.22
5	750	0.276
6	900	0.183
7	1050	0.228
8	1200	0.170
9	1350	0.207

Table 8. The voltages of the bus after capacitor placement

Scenario	Voltage
1	0.993
2	0.9874
3	0.967
4	0.948
5	0.917
6	0.908
7	0.889
8	0.859
9	0.834

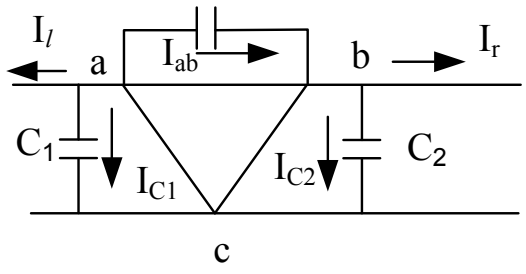

Figure 1. Power factor correction in a three-phase circuit by using shunt capacitors

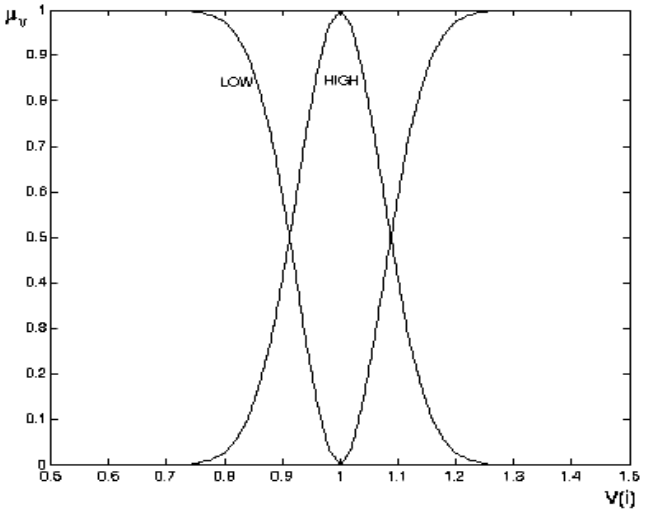

Figure 2. Voltage sensitivity membership function(μv)

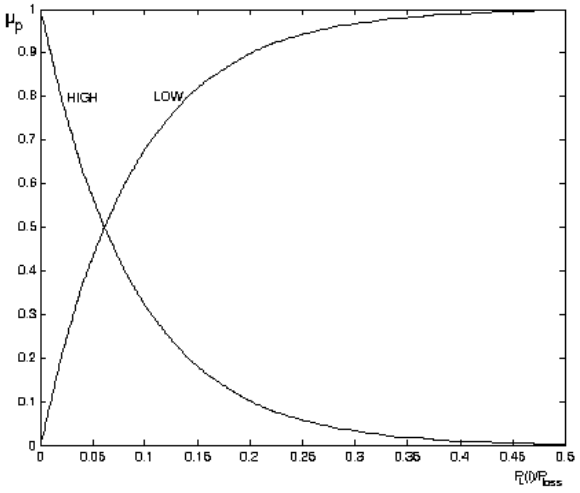

Figure 3. Loss membership function(μp)

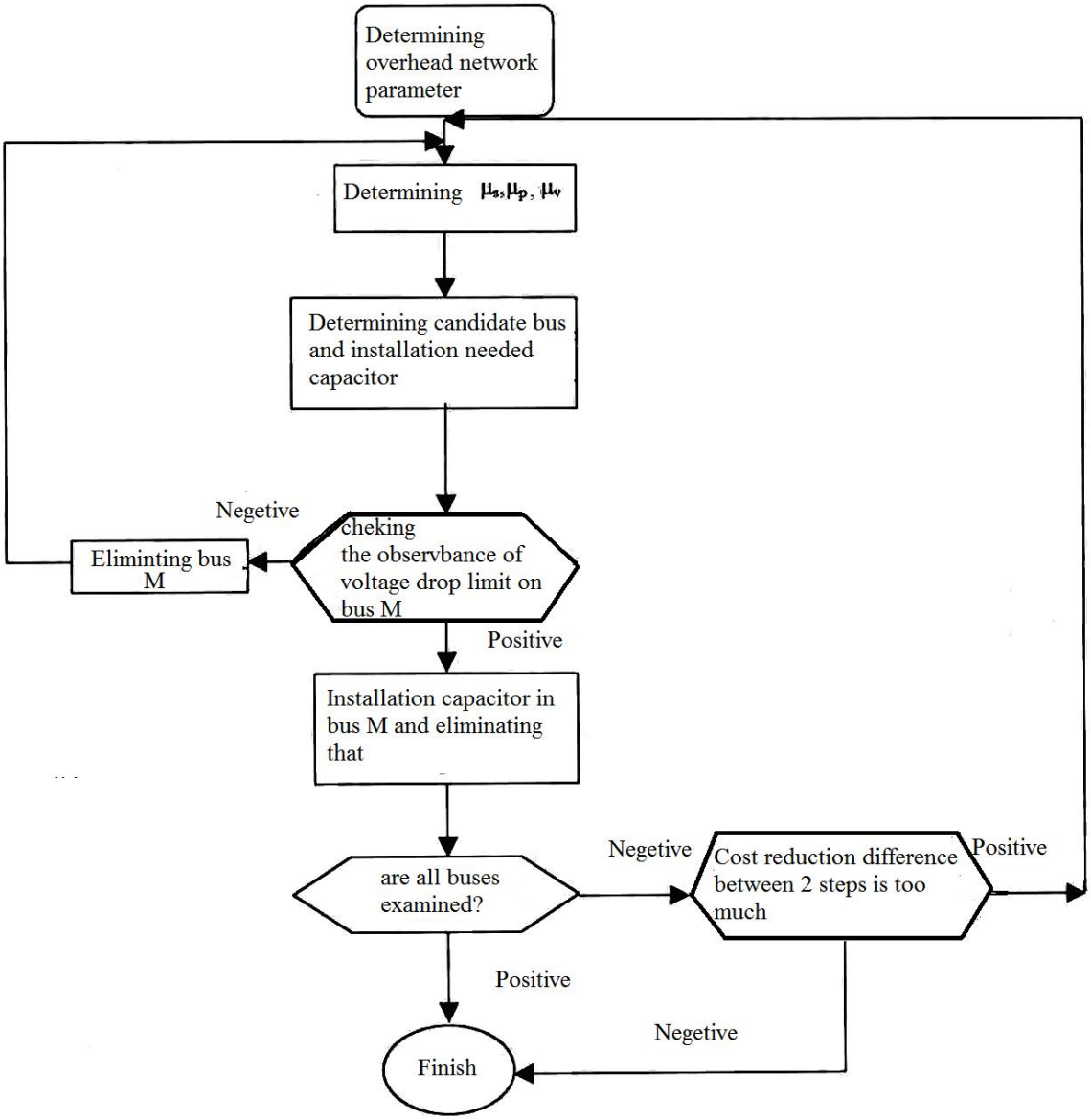

Figure 4. Flowchart of the optimum capacitor allocation procedure in the electric railway overhead network

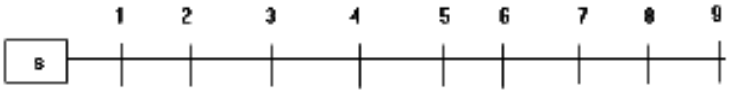

Figure 5. Single line diagram of radial feeder of the assumed overhead network